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# Kinematics Modeling and Simulation of SCARA Robot Arm

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**ABSTRACT:** *Pick and place task is one among the most important tasks in industrial field handled by "Selective Compliance Assembly Robot Arm" (SCARA). Repeatability with high-speed movement in horizontal plane is remarkable feature of this type of manipulator. The challenge of design SCARA is the difficulty of achieving stability of high-speed movement with long length of links. Shorter links arm can move more stable. This condition made the links should be considered restrict then followed by restriction of operation area (workspace). In this research, authors demonstrated on expanding SCARA robot's workspace in horizontal area via linear sliding actuator that embedded to base link of the robot arm. With one additional prismatic joint the previous robot manipulator with 3 degree of freedom (3-DOF), 2 revolute joints and 1 prismatic joint is become 4-DOF PRRP manipulator. This designation increased workspace of robot from 0.5698m$^2$ performed by the previous arm (without linear actuator) to 1.1281m$^2$ by the propose arm (with linear actuator). The increasing rate was about 97.97% of workspace with the same links length. The result of experimentation also indicated that the operation time spent to reach object position was also reduced.*

***KEYWORDS –*** *Stability,Inear sliding actuator, PRRPManipulator,Industrial Robotics,Kinematics.*

## I. INTRODUCTION

Robots have wide range applications in today's industry. They are designed in many different forms according to desire tasks. With specification of small application area and electrically driven, Selective Compliance Assembly Robot Arm (SCARA) is been classified as a type of assembly manipulator. Most industrial SCARA robots at the present time are fall into cylindrical geometric type, with three degrees of freedom (two revolute joints and one prismatic joint) they are called RRP manipulator [1]. Assembly and packing are among well-known pick-place tasks handled by SCARA robot [2]. Effective of tasks including accuracy, repeatability, rapidly and stability are very important in context of industrial automations. The one thing that occurred following all these features is restriction of workspace. Natural manner of movement while the link length increased the stability and rapidly of movement is reduced and vice versa. This paper invested with development of SCARA robot arm by adding a linear sliding actuator to increase workspace without with the same links length so that other specifications could keep non-change. In section II the movement was then studied with implement of kinematics theory of manipulator and structure design was presented with joints and links description in section III. Control system is based on microcontroller and interface performing via Rs-485 serialcommunication port. The expansion of workspace and the cycle time reducing is indicated with the experimentation results in the last section.

## II. KINEMATIC MODELING

Kinematics is the science of motion that treats the subject without regard to the forces that cause it [3]. In this research, two kinds of kinematics were implied in very important role to analyze motion of robot. Forward kinematics is process of determination the position and orientation of end effector given values for joints variables of robot. Inverse kinematics is inverse process that determines values of joints variables for given position and orientation of robot's end effector [3]. The Denavit-Hartenberg (D-H) model of representation or can be called Denavit-Hartenberg convention was applied in forward kinematics method to determine modeling robot links and joints.

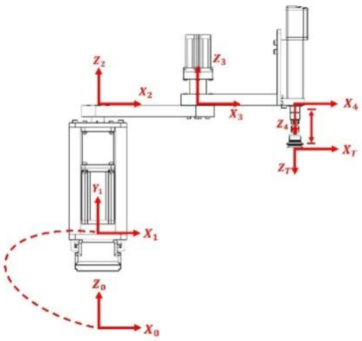


Fig. 1. Frame assignment

With rigidly attached frame assigned as shown in Figure 1 the D-H parameters obtained in Table 1.

| i | $a_{i-1}$ | $\alpha_{i-1}$ | $d_i$ | $\vartheta_i$ |
|---|---|---|---|---|
| 1 | 0 | π/2 | $d_1$ | 0 |
| 2 | 0 | -π/2 | $l_1$= 0.363m | $\theta_2$ |
| 3 | $l_2$= 0.265m | 0 | 0 | $\theta_3$ |
| 4 | $l_3$= 0.2536 m | π | $d_4$ | 0 |
| 5 | 0 | 0 | $d_5$ = 0.11m | 0 |

TABLE 1

Denavit-Hartenberg Parameters

## 2.1 Forward Kinematics

To determine forward kinematics, we started from writing transformations matrix for each frame.

Using general form of transformations matrix that transforms vectors defined in {i} to their description in {i-1} like this [4]:

$$ {}^{i-1}_{i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1} d_i \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Substituting parameters from Table 1 in equations (1), the transformation matrix for each link are formed as below:

$$ {}^{0}_{1}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -d_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

$$ {}^{1}_{2}T = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ 0 & 0 & 1 & l_1 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

$$ {}^{2}_{3}T = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & l_2 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

$$ {}^{3}_{4}T = \begin{bmatrix} 1 & 0 & 0 & l_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & -d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5) $$

$$ {}^{4}_{T}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6) $$

The link transformation that relates frame {T} to frame {0} can be derived by multiplying (2), (3), (4), (5) and (6) together

$$ {}^{0}_{T}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{T}T \quad (7) $$

$$ {}^{0}_{T}T = \begin{bmatrix} c_{23} & -s_{23} & 0 & l_2c_2 + l_3c_{23} \\ s_{23} & c_{23} & 0 & l_2s_2 + l_3s_{23} - d_1 \\ 0 & 0 & -1 & l_1 - d_4 - d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8) $$

Format (8) to be simple form as:

$$ {}^{0}_{T}T = \begin{bmatrix} c_\phi & -s_\phi & 0 & x \\ s_\phi & c_\phi & 0 & y \\ r_{31} & r_{32} & -1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9) $$

Where

$$ \begin{bmatrix} x \\ y \\ z \\ \phi \end{bmatrix} = \begin{bmatrix} l_2c_2 + l_3c_{23} \\ l_2s_2 + l_3s_{23} - d_1 \\ l_1 - d_4 - d_5 \\ \theta_2 + \theta_3 \end{bmatrix} \quad (10) $$

Nomenclatures of all parameters are listed in Table 2 below [5]:

TABLE 2

Parameter nomenclature

| Symbol | Description | Unit |
|---|---|---|
| $a_{i-1}$ | The distance from $\hat{Z}_i$ to $\hat{Z}_{i+1}$ measured along $\hat{X}_i$ | m |
| $\alpha_{i-1}$ | The angle from $\hat{Z}_i$ to $\hat{Z}_{i+1}$ measured about $\hat{X}_I$ | rad |
| $d_i$ | The distance from $\hat{X}_{i-1}$ to $\hat{X}_i$ measured along $\hat{Z}_i$ | m |
| $\theta_i$ | The angle from $\hat{X}_{i-1}$ to $\hat{X}_i$ measured about $\hat{Z}_i$ | rad |
| ${}^{i-1}_{i}T$ | Transformations matrix that transforms vectors defined in{i} to their description in{i-1} | - |
| $t_2$ | $\tan\theta_2$ | - |
| $c_2$ | $\cos\theta_2$ | - |
| $s_2$ | $\sin\theta_2$ | - |
| $c_{23}$ | $\cos(\theta_2+\theta_3)$ | - |
| $s_{23}$ | $\sin(\theta_2+\theta_3)$ | - |
| x | $\hat{x}$ vector of end effector attached frame related to zero frame | m |
| y | $\hat{y}$ vector of end effector attached frame related to zero frame | m |
| z | $\hat{z}$ vector of end effector attached frame related to zero frame | m |
| $\theta$ | Rotation angle of end effector attached frame related to zero frame | rad |

### 2.2 Inverse Kinematics

Inverse kinematics of robot derived by solving for values of two joints parameters ($\theta_2$, $\theta_3$) and values of two links parameters ($d_1$, $d_4$).

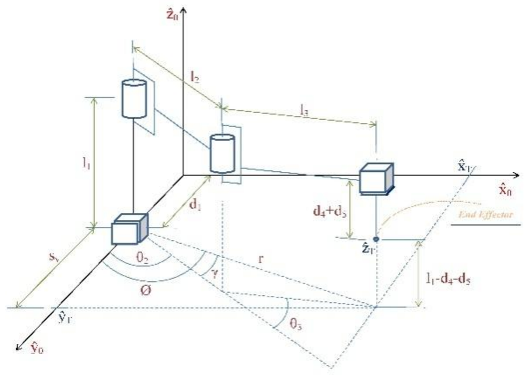

Fig. 2. SCARA manipulator geometric model

Applying the geometric representation of robot like in Figure 2, while the coordinate of the end effector frame origin $o_T[x_T,y_T,z_T]$ was given we got these relationships of variables:

$$\begin{cases} d_4 = l_1 - z_T - d_5 \\ d_1 = y_T - s_y = where\ s_y = l_2 s_2 + l_3 s_{23} \\ \theta_3 = a\tan 2(\pm\sqrt{1-c_3^2}, c_3)\ where\ c_3 = \dfrac{s_y^2 + x_T^2 - l_2^2 - l_3^2}{2 l_2 l_3} \\ \theta_2 = a\tan 2(s_y, x_T) - a\tan 2(l_3 s_3, l_2 + l_3 c_3) \end{cases}$$

With these relationships, the only one parameter that can be solved is $d_4$, where others three parameter is depended on each other and related to two coordinate values of robot's end effector ($x_T$, $y_T$). Three equations with 3 unknown values, just two given $x_T$ and $y_T$ would not enough to solve these equations. In this case, a solution proposed for this is to give an arbitrary value for $d_1$. Three levels of $d_1$ is applied ($d_1$= 0, 0.30, 0.60). The value of $s_y$ was solved by the relation $s_y = y_T - d_1$, eventually the equations $\theta_3 = a\tan 2(\pm\sqrt{1-c_3^2}, c_3)$ and $\theta_2 = a\tan 2(s_y, x_T) - a\tan 2(l_3 s_3, l_2 + l_3 c_3)$ could be solved for value of $\theta_3$ and $\theta_2$ respectively.

Note that $\theta_2$ and $\theta_3$ could be obtained by solving cosine equation, but to make sure the exact quadrant of which the robot end effector located the atan2 function was been used. The coordinate in Figure 2 is defined by left-handed coordinate where left thumb points along the Z axis in a positive Z-direction and the curled fingers of the left hand represent a motion from the first or X axis to the second or Y axis. This coordinate system makes it more convenient to see details of the system and easier to analyze.

## III. STRUCTURE DESIGN

### 3.1 Design of joints and links

The design of this robot manipulator was to

extend application area or can call workspace to make it capable to deal with pick and place task in wider area with same length of each link. Idea of designing is based on principle of normal SCARA robot just to add one more link at the base of robot arm. With this principle the previous robot arm with fix base link was become sliding base arm. Detail of all links and joints are gathered in Table 3 and Table 4 respectively.

TABLE 3
Joints Specifications

| Joint No. | Description | Detail |
|---|---|---|
| joint 1 | Prismatic joint that powered by servo motor and actuated by ball screw | Slide forward/backward 0.60m in horizontal axis |
| joint 2 | Revolute joint actuated by stepper motor | Rotate about vertical axis 11/9π(rad) |
| joint 3 | Revolute joint actuated by stepper motor | Rotate about vertical axis 13/9π(rad) |
| joint 4 | Prismatic joint powered by stepper motor and actuated by ball screw | Move up/down 0.1m in vertical axis |

TABLE 4
Links Specifications

| Link No. | Description | Dimension(m) | Weight (Kg) |
|---|---|---|---|
| Link0 | Linear ball screw | 0.05 x 0.6 (diameter x length) | 6.233 |
| Link1 | Rigid body made from carbon iron | 0.15 x 0.15 x 0.30 (wide x depth x height) | 20.214 |
| Link2 | Rigid body made from Aluminium alloy | 0.085 x 0.265 x 0.03 (wide x depth x height) | 2.953 |
| Link3 | Rigid body made from Aluminium alloy | 0.09 x 0.2536 x 0.03 (wide x depth x height) | 5.375 |
| Link4 | Linear ball screw | 0.022 x 0.1 (diameter x length) | 1.733 |
| End effector | Vacuum pad actuated by pneumatic system to create suction | 0.04 x 0.011 (diameter x length) | 0.15 |

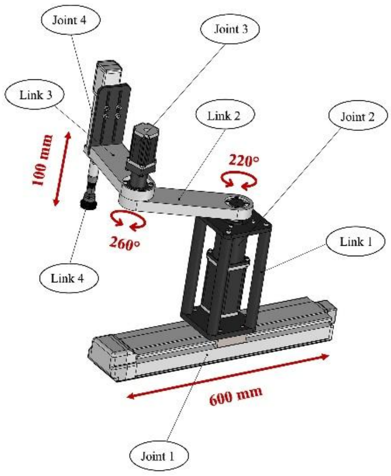


Fig. 3. SCARA robot with linear sliding actuator

### 3.2 Basic Specifications

As mentioned previously all components of structure was kept no change (except linear sliding actuator that embedded to base of robot arm). Thus, robot could reach the maximum distance of 0.5186m (measurefrom base frame of robot while the link2 and link3 are maximum extended), that is equal to combination the length of link2 and link3 together (l2+l3). Linear sliding actuator that let robot move in horizontal axis has very little effect on capability of lifting load, so payload of robot is still unchanging (1.5kg maximum). Velocity of the robot is divided into two parts (linear velocity and angular velocity) that are shown in Table 5 Torque required for motors to move each joint is shown in Table 6.

TABLE 5

Robot's Velocity

| Joint No. | Linear velocity(m/s) | Angular velocity(rad/s) |
|---|---|---|
| 1 | 1.000 | - |
| 2 | 1.040 | 3.927 |
| 3 | 1.138 | 4.488 |
| 4 | 1.800 | - |

TABLE 6
Torque Required

| Motor No. | Torque required without load(N.m) | Torque required with maximum load(N.m) |
|---|---|---|
| 1 | 0.109 | 0.118 |
| 2 | 10.121 | 11.416 |
| 3 | 2.199 | 2.611 |
| 4 | 0.022 | 0.076 |

All values in Table 5 and Table 6 were measured in maximum. Torques required by motor2 and motor3 were 10 times reduced from the actual torques needed to make joint 2 and joint 3 move, that’s the result of using gearbox with gear ratio of 1:10.

### 3.3 Workspace Expansion

The previous SCARA robot (without linear sliding actuator) could operate the tasks in workspace that while projected in horizontal plane is area that covered by the solid line in Figure 4, the area of this area is 0.5698m$^2$.

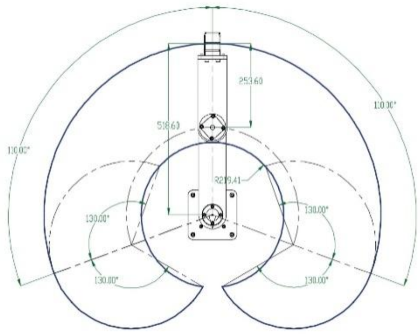

Fig. 4. SCARA robot’s workspace without linear sliding actuator

By embedding one linear sliding actuator to the base of the robot, the workspace was expanded as shown in Figure 5. The area of this cross section is 1.1281m$^2$, that’s 97.97% larger than the previous one.

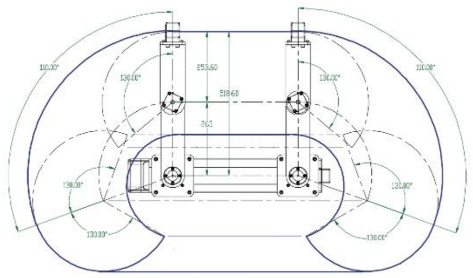

Fig. 5. SCARA robot’s workspace linear sliding actuator

## IV. CONTROL UNIT OF SCARA ROBOT

PC-Based control method with a motion controller installed and interface with PC via PCI bus interface is one of the most effective control system in assembly industrialrobotic [7]. This method of control needs massive costs due to the high price of components. With the costs restricted the proposed method is not appropriate. The control method in this research is a microcontroller-based system. According to operate behavior of microcontroller, which process all command sequentially, one microcontroller board is not enough to make all joint move together at the same time. Thus, four of microcontroller board (ARDUINO) is used together to control movements of stepper motor on each joint.

One of those four microcontroller board is used as main or master board that control whole process of robot movements, where other three boards are used as slave that receive commands from master to control stepper motor through stepper driver.

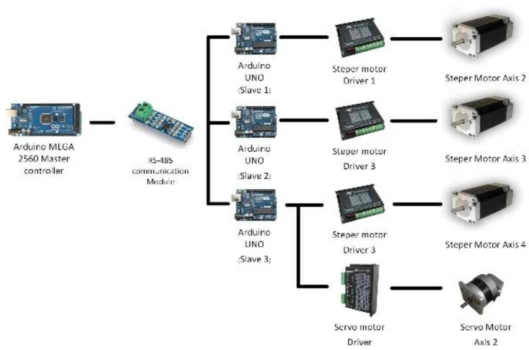

Fig. 6. System overview of SCARA robot’s control unit

Principle of controlling is each motor of revolute joint is controlled by one slave board, while two remaining motors of prismatic joint are controlled together by other one board. Following this principle, the system has three microcontroller

boards that control motor separately. In this case, to make all motors move simultaneously, communication between boards is needs. RS485 protocol is used here for serial communication between boards, where MAX485 modules took the role of interfacing. Using just two wires for multiple board connection, it's one among convenient way of communication. The idea of this system is taken from [6], where microcontroller used is 80C15. Although this system might not as effective as the proposed PC-based one, it can work in medium level of effective, while compare to the costs is really worth to invest. The overview of control system is shown in Figure 6.

## V. EXPERIMENTS

Robot was tested to move to 300 different positions to determine cycle time of operations. The positions chose located in area where could be reach by both types of robot arm (with and without linear sliding actuator). Half circle area at the right-hand side in Figure 5 could be reach by both arms with same cycle time was not suitable for this experiment, where the half circle area at the left-hand side could not reach by the robot arm without linear sliding actuator should also been rejected. The central area was considered as suitable area for the experiment. Displacement of linear sliding actuator ($d_1$) applied in this experiment was the second level (0.30m). The result shown inFigure 7, where we can see the different time spent for the same positions reached.

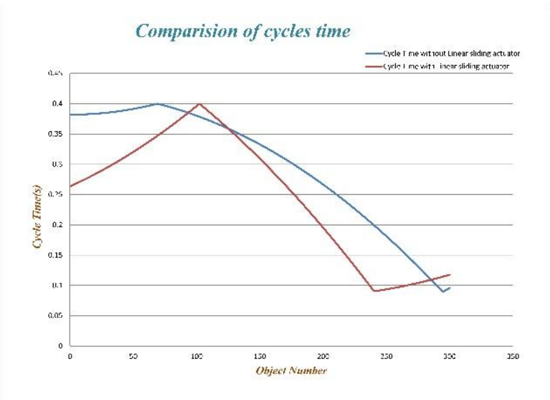


Fig. 7. Operation time comparison

This result show that after embedded linear sliding actuator to robot arm, the operation time for most position has been reduced.

## VI. CONCLUSION

This paper has proposed the development of SCARA robot by embedding one more axis at the base link of robot arm. The previous robot with 3-DOF has become the 4-DOF arm with two prismatic joints and two revolute joints. The design of control unit has proposed that based on microcontroller and RS485 interface. Complexity of kinematics model has been analyzed with the solution of forward kinematics derived by the convention of Denavit-Hartenberg and inverse kinematics analyzing derived by applying geometric model of manipulator. The effective of development were indicated in experiments that the result obtained in increasing of robot's workspace and reducing cycle time of operation task.

## VII. Acknowledgements

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